

Variability of the Ap Star HD 9996

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ABSTRACT

We present here new measurements of the longitudinal magnetic field (B_e) in the binary system HD 9996, where the primary companion is an Ap star. Series of 63 B_e observations was obtained in years 1994–2011 with the 1-m optical telescope of the Special Astrophysical Observatory (Russia). New magnetic data allowed us to refine the long-term magnetic period of HD 9996 to $P_{\text{mag}} = 21.8$ years. Compilation of archival photometric data showed the existence of long-term variations of HD 9996 in time scale of 22–23 yr consistent with P_{mag} . We identify P_{mag} with the precession period of the primary Ap star and summarize search for a short-term rotational period and the rotational line broadening in this star.

Key words: Stars: chemically peculiar – Stars: individual: HD 9996 – Stars: magnetic fields

1. Introduction

The star HD 9996 (HR465, GY And), spectral type B9p CrEuSi belongs to the subclass of long-period magnetic Ap stars. Compilation of early photometric measurements for HD 9996 allowed one to constrain the corresponding period P in the range $7750 < P_{\text{ph}} < 8550$ days, or $21.2 < P_{\text{ph}} < 23.4$ years (Pyper and Adelman 1986). First measurements of the effective (longitudinal) magnetic field B_e in HD 9996 were initiated by Babcock (1958) who used the photographic method for recording of magnetically split spectral lines. Further measurements of B_e were published by Preston and Wolff (1970) and Scholz (1978, 1983), who used the same method.

Our new magnetic measurements of HD 9996 were the result of a large-scale observational program for measuring magnetic fields in stars, which was performed at the Special Astrophysical Observatory of the Russian Academy of Science. The program used 6-m optical telescope and the hydrogen-line magnetometer (Bychkov 2000). Series of B_e observations for this star was published by Bychkov *et al.*

(1997), who improved the magnetic period and obtained $P_{\text{mag}} = 7842$ days, or 21.5 yr. However, there existed a large uncertainty regarding both the exact value of that period and the character of the magnetic variations B_e vs. time, which did not form a simple sine-wave as was in the oblique-rotator model.

From that time two of us (VDB and LVB) continued monitoring of the magnetic field strength B_e of HD 9996. This paper presents results of this 18 yr observing run.

2. Instrumentation and Data Processing

HD 9996 is a relatively bright object with the apparent visual magnitude $V = 6.38$ mag. Therefore, magnetic monitoring of this star was performed in coude focus of the 1-m reflector at SAO, equipped with the CEGS spectrometer and analyzer of circular polarization (*cf.* Bychkov 2008).

In this research we obtained high quality CCD spectra of the star with $R = 45000$, $S/N \approx 40$ or even more, which were processed with MIDAS software. Values of the longitudinal magnetic field B_e were determined with the standard procedure consisting of the following steps.

1. Computer code STARSP (Tsybmal 1996) generated synthetic spectrum of the star, using the database VALD (Kupka *et al.* 1999). Then, we selected a set of spectral lines suitable for further measurements.
2. Gaussians were fitted by the least squares method to the observed profiles both in clockwise (RCP) and counterclockwise (LCP) circularly polarized light. We ignored lines which exhibited registration defects due *e.g.*, to cosmic rays. Line splitting caused by the longitudinal magnetic field was set to the separation of the weight centers of both circularly polarized Gaussian profiles.
3. Intensity of the effective magnetic field was derived from the separation of both polarized components of each line following the well-known relation

$$\lambda_L - \lambda_R = 2 g_{\text{eff}} 4.67 \times 10^{-13} \lambda_0^2 B_e, \quad (1)$$

where the wavelength λ_0 was expressed in Å and the magnetic field intensity B_e in G.

The final value of B_e was the arithmetic mean of the intensities taken over all useful spectral lines in a given spectrum. We estimated the standard deviation σ of B_e assuming normal distribution of all errors.

Instrumental effects were taken into account following Bychkov, Romanenko and Bychkova (2000). During each observing night we performed measurements of the magnetic standard stars, α^2 CVn and 53 Cam, as well as two standard stars of “null” magnetic field, α CMi, α Boo, also the Moon etc. Measurements of B_e for “standard” stars were in a good agreement with the data collected in the literature.

The above observational and calibration procedures and reduction of raw data were also described in Bychkov, Bychkova and Madej (2006).

3. Observations

In 2005 (JD 2453370.+) we collected 39 new B_e observations of HD 9996 and determined the period of magnetic variability $P_{\text{mag}} = 7\,692$ days (Bychkov *et al.* 2005).

Table 1

Magnetic field measurements B_e of the Ap star HD 9996 obtained with the 1-m telescope
SAO RAS

JD2400000.+	B_e	σ_{B_e}	JD2400000.+	B_e	σ_{B_e}
49649.378	−2231	92	54779.3493	+385	84
50022.301	−1730	82	54781.3159	+609	59
50022.347	−1800	78	54783.2618	+529	65
50023.388	−1683	69	55080.4590	+145	106
50064.282	−1831	86	55081.4097	+509	39
51535.2986	−146	69	55082.3777	+23	59
51536.2139	−361	59	55083.4833	+216	72
51890.251	+214	124	55142.3229	+966	79
53273.569	+670	71	55164.2991	+162	93
53275.622	+453	99	55494.3313	−59	52
53276.613	+552	120	55494.3736	−60	61
53278.602	+723	90	55495.3951	−217	104
53279.616	+843	95	55553.1340	−140	60
53626.484	+547	90	55553.1763	−141	59
53629.500	+707	86	55554.1263	−180	67
53632.401	+721	99	55554.1631	−181	61
53636.373	+583	147	55555.1187	−81	70
53637.348	+611	84	55555.1548	−82	58
53638.377	+740	120	55584.1423	−107	59
53665.342	+268	118	55584.1861	−111	73
53666.289	+382	105	55819.5076	−467	47
53667.297	+821	84	55819.5437	−469	53
53668.312	+488	132	55823.5305	−401	102
53692.259	+431	92	55823.5673	−403	130
53718.171	+566	101	55852.3381	−484	50
53719.197	+443	120	55852.3777	−486	43
53721.199	+317	101	55852.4138	−488	74
54112.126	+771	111	55881.3333	−420	42
54373.4118	+633	101	55881.4194	−424	49
54374.3722	+676	122	55911.2875	−500	95
54429.2590	+827	74	55911.3159	−502	78
54430.2500	+998	71			

Since the magnetic phase curve was still poorly constrained, the monitoring project for HD 9996 was continued until now. Finally, we collected 63 measurements of B_e during the last 18 years. All our observations of B_e are shown in Table 1. Thus the total span of observations of B_e in HD 9996 amounts to 62 years, or almost 3 full magnetic periods P_{mag} .

Fig. 1 presents the measured values of the effective magnetic field B_e for HD 9996 as a function of time (Julian Day).

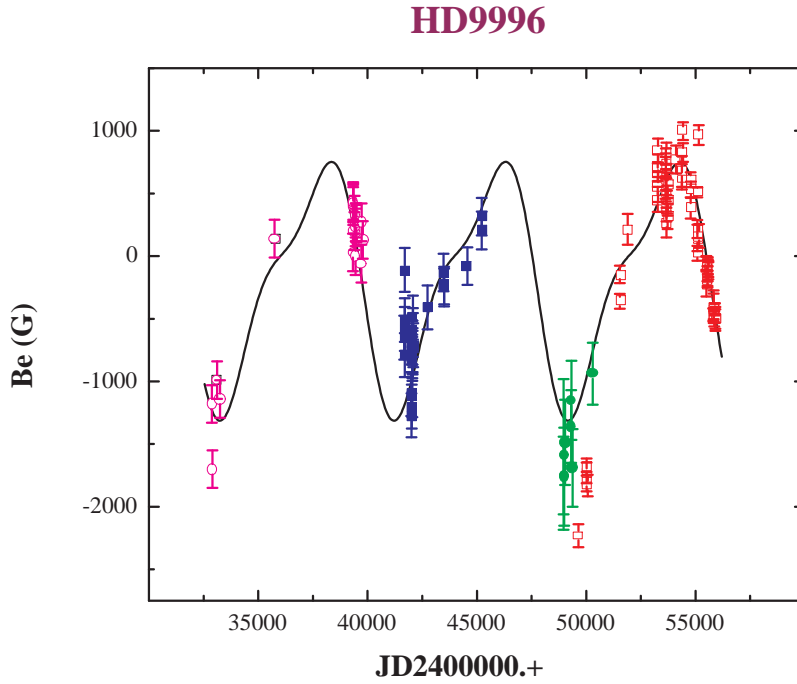


Fig. 1. Longitudinal magnetic field B_e for HD 9996 vs. Julian Day in the years 1946–2011. Observations are colored depending on the source: magenta – Babcock (1958), purple – Preston and Wolff (1970), blue – Scholz (1978, 1983), green – Bychkov *et al.* (1997) 6-m telescope; red – this paper (Table 1) 1-m telescope. Series of discrete B_e points are overlayed by the best fitted double sine phase curve.

We attempted to improve the magnetic period of HD 9996 using all the available B_e measurements, though the distribution of all B_e points vs. Julian Day is not well suited for the period analysis. We obtained the best value $P_{\text{mag}} = 7961.8 \pm 22$ days, or 21.8 years. Zero phase of B_e variations was set to the time T_0 of minimum magnetic field strength, $B_e(\text{min})$. The best fit yielded $T_0 = 2433240.7$ JD (see the following sections).

The corresponding smooth curve approximating all available B_e points was defined by Eqs. (2)–(3) and it is plotted in Figs. 1–2.

4. Magnetic Phase Curves

4.1. Long-Term Variations

We approximated variations of the effective magnetic field of HD 9996, B_e vs. time t by a double sine wave (Bychkov *et al.* 2005)

$$B_{ei}(\phi) = B_0 + B_1 \cos(\phi + z_1) + B_2 \cos(2\phi + z_2) \quad (2)$$

where phase ϕ

$$\phi = 2\pi \frac{T_i - T_0}{P_{\text{mag}}}. \quad (3)$$

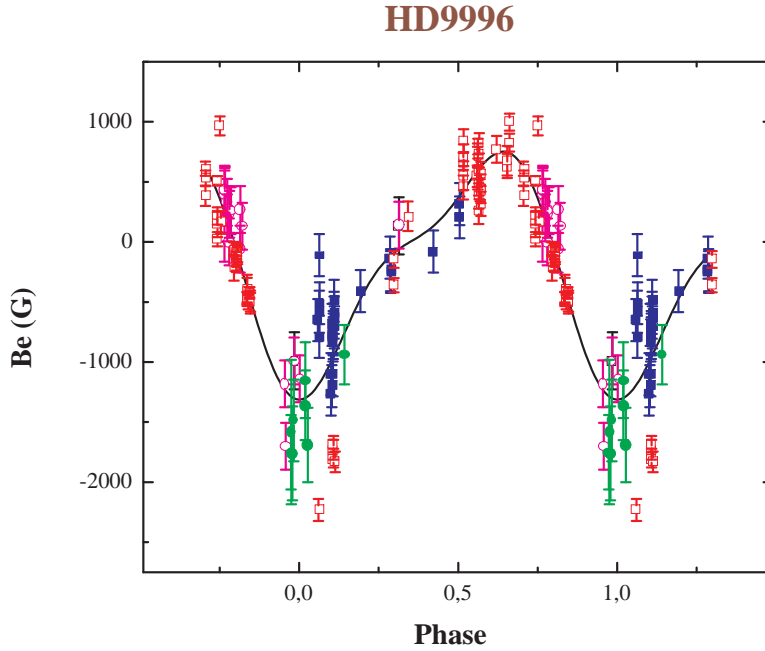


Fig. 2. Magnetic phase curve $B_e(\phi)$ computed for the principal period $P_{\text{mag}} = 7961.8$ days = 21.8 years. All the existing observations spanning 1946–2011 were taken into account here. The color coding is the same as in Fig. 1.

Fig. 2 presents the magnetic phase curve $B_e(\phi)$ which was computed for the period $P_{\text{mag}} = 7961.8$ days and the zero epoch $T_0 = 2433240.7$ JD. Points B_e on the curve are nonuniformly distributed in phase ϕ . Moreover, the points close to the phase $\phi \approx 0$ are significantly scattered. Such a scatter suggests that the observed variations of the longitudinal magnetic field B_e in HD 9996 were caused by superposition of a few processes with significantly differing periods.

One should note that the earliest magnetic field measurements B_e were performed with the photographic technique of low accuracy. The corresponding points in Figs. 1–2 exhibit a rather large dispersion along the vertical axis. Due to that,

only our newest photoelectric B_e measurements of HD 9996 from the last 18 years are the most significant and were analyzed in this paper (*cf.* also Bychkov *et al.* 1997, 2005).

Table 2

Parameters of the long-term magnetic variability of HD 9996. They define phase curve plotted in Fig. 3, which was obtained only from our new observations presented in Table 1.

Parameter	value
T_0	JD 2449478.4
P_{mag}	7961.8 days
B_0	415 G
B_1	1311 G
z_1	0.985
B_2	315 G
z_2	0.019

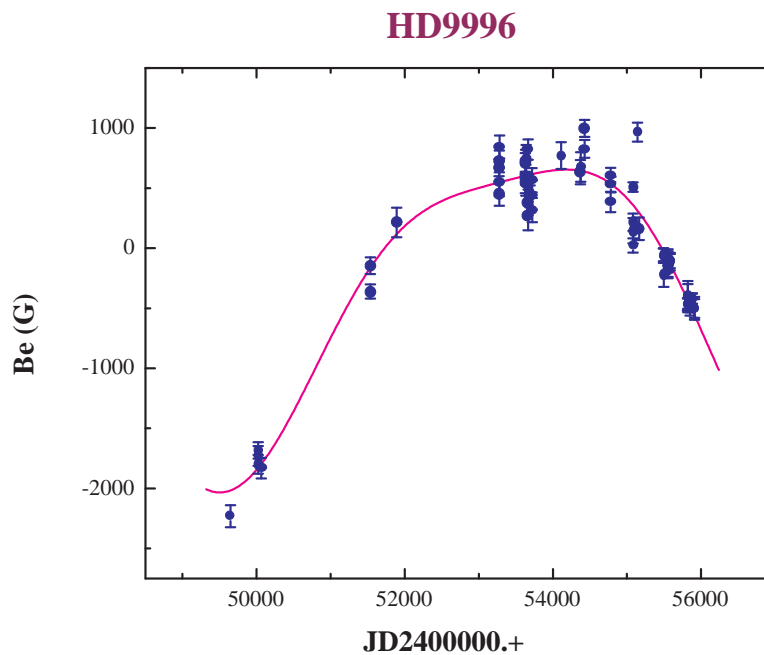


Fig. 3. Magnetic field measurements obtained with the 1-m telescope as a function of JD and magnetic phase curve, according to Eq. (2) – solid line.

Fig. 3 shows the individual B_e observations and error bars, which were obtained at the Coude focus of the 1-m telescope at SAO RAS and the instrumentation: 1-m telescope + GECS + ACP (with the subtraction of instrumental polarization). Fig. 4 shows the magnetic phase curve $B_e(\phi)$ derived only from our photoelectric measurements of the last 18 years. In such a manner we obtained a homogeneous

series of B_e points of a fairly high accuracy, see Table 1. Parameters of the phase curve are given in Table 2.

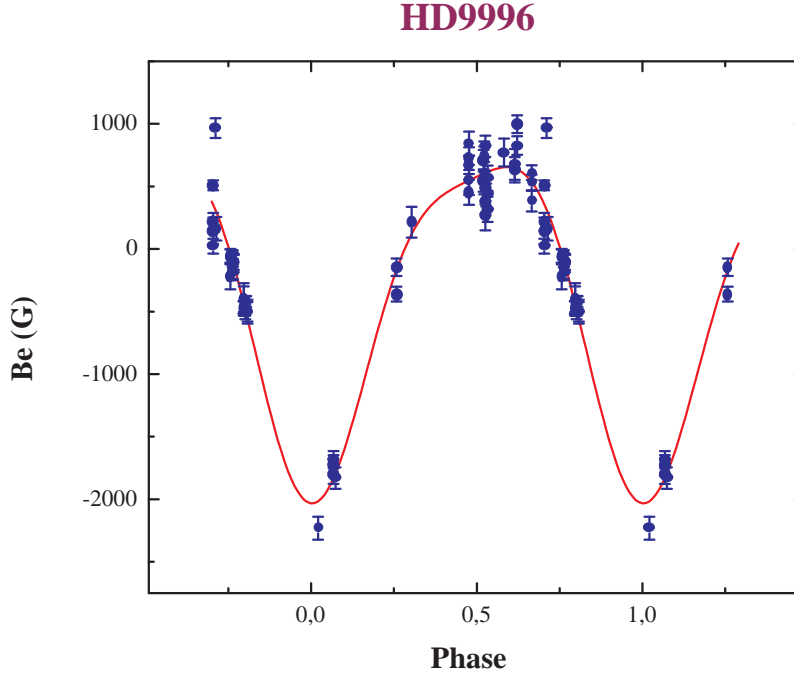


Fig. 4. Magnetic phase curve $B_e(\phi)$ computed for the same period $P_{\text{mag}} = 7961.8$ days. The phase curve was derived only from our observations obtained at the 1-m telescope of SAO RAS.

4.2. Search for Short-Term Variations

Single-lined spectroscopic binary star HD 9996 is a rather wide pair with the orbital period of $P_{\text{orb}} = 272.99$ days. Orbital elements of that system are presented in Table 3, following Scholz (1978). Unfortunately, errors of orbital elements were not given in his paper.

Carrier *et al.* (2002) determined the new orbital parameters for HD 9996, with $P_{\text{orb}} = 272.88 \pm 0.20$ days, $T_{\text{per}} = \text{JD } 2444492.34 \pm 2.24$ and $e = 0.532 \pm 0.023$. Both old and new periods P_{orb} and the resulting orbital phases differ marginally, by less than the corresponding errors.

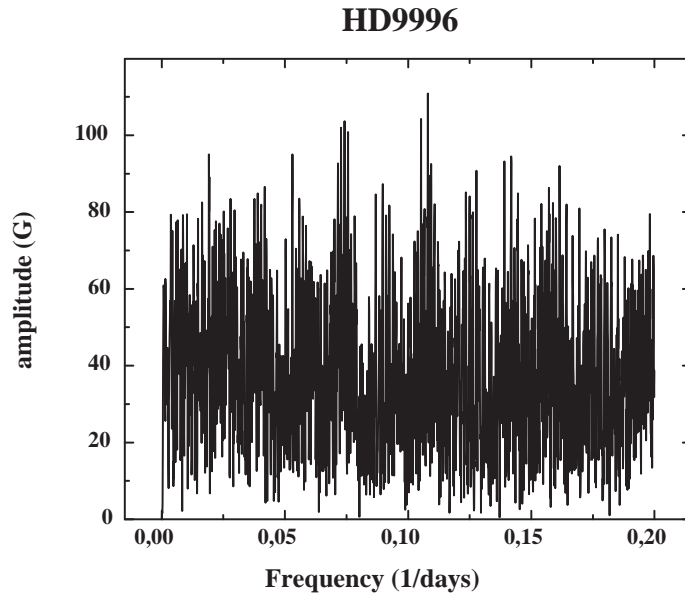
In order to investigate the short-term B_e variations we subtracted the double-wave defined by Eq. (2) from the 18 year series of our B_e measurements. Long $P_{\text{mag}} = 7961.8$ days = 21.8 years period was applied here. Spectral analysis of such a prewhitened B_e time series produced a white frequency spectrum with no features for frequencies $f \leq 0.2 \text{ day}^{-1}$. This result excluded the existence of periodic B_e variations in HD 9996 with periods $P \geq 5$ days and full amplitude ≥ 200 G, see Fig. 5.

Table 3

Orbital elements of the binary system HD 9996 after Scholz (1978)

Parameter	Value
e	0.47
ω	$17^\circ.7$
K	11.3 km/s
γ	-0.35 km/s
T_{per}	JD 2442048.03
$a \sin i_{\text{orb}}$	37.4×10^6 km

Parameter T_{per} denotes the time of periastron passage.

Fig. 5. Amplitude spectrum of the prewhitened time series of all our B_e measurements (see Table 1).

In particular, there exist no detectable variations of the longitudinal magnetic field B_e with the orbital period $P_{\text{orb}} = 272.99$ exceeding observational error, the latter of the order of 100–200 G. Such an observation implies that the influence of the secondary on the primary Ap star is rather weak due to a large separation. On the other hand, the secondary on highly eccentric orbit still produces a periodic mechanical impact on the Ap component at the moment of periastron passage.

Results of the spectral analysis of our B_e time series was performed following the method by Kurtz (1985) and with the original numerical code supplied by the author. As can be seen from Fig. 5 there is no trace of the period below the frequency $f \leq 0.2 \text{ d}^{-1}$ with a half amplitude bigger than ≈ 100 G.

5. Photometry

5.1. Long-Term Variations

HD 9996 shows extremely slow magnetic, spectral and photometric variations, which was noted by Preston and Wolff (1970). They found a slow decline of V magnitude for HD 9996 by 0.1 mag, compared to UBV observations by Abt and Golson (1962) and Stępień (1968), which were made 8 years apart. Preston and Wolff (1970) concluded that the brightness of HD 9996 varies with the period of 22–24 years.

The early three-color photometric observations of HD 9996 were also published by Osawa and Hata (1962), but their results apparently came unnoticed by Preston and Wolff in their paper.

Dumont and Le Borque (1983) appended new observations of HD 9996 which originally were obtained in the Geneva photometric system and were transformed later to the Johnson V and $B - V$ magnitudes. They compiled all previous observations and eventually confirmed the possibility of a 22–24 year period.

The newest V observations were compiled by Pyper and Adelman (1986). Apparent luminosity of HD 9996 in these years varied in the range $V = 6.29 - 6.41$ mag.

Fig. 6 shows all the available V observations against Julian Day (upper panel), including those obtained from the Hipparcos catalog (see Section 5.3). For a comparison, the lower panel of Fig. 6 presents all the existing magnetic B_e measurements vs. JD.

5.2. Short-Term Variations: Ground-based UBV observations

Winzer (1974) claimed the existence of another photometric period in HD 9996, $P_{\text{ph}} = 36.5$ days. This result was also quoted in the catalog of periods of Ap stars by Catalano and Renson (1984). Photometry by Rakosch and Fiedler (1978) gave much less conclusive results. Nevertheless, they constrained the period to $P_{\text{ph}} = 35 - 40$ days, based on a rather scarce set of their B and V magnitudes.

Rakosch and Fiedler (1984) constrained amplitudes of short-term light variations to $\Delta U = 0.012$ mag, $\Delta B = 0.065$ mag and $\Delta V = 0.050$ mag, respectively. They presented the fine run of U magnitudes vs. time, which suggested that the U luminosity was nearly constant over about 100 days of observations, except for a small systematic increase of U .

5.3. Short-Term Variations: Hipparcos Photometry

Hipparcos catalog contains time series of 90 H_P magnitudes of HD 9996 measured during 3.5 years. Photon-counting tube device at the satellite measured the brightness of stars in its own broad-band photometric system, with the peak response at about 4500 Å and a wide wing redwards. Obviously, H_P magnitude of a star can differ slightly from its V brightness in the Johnson system.

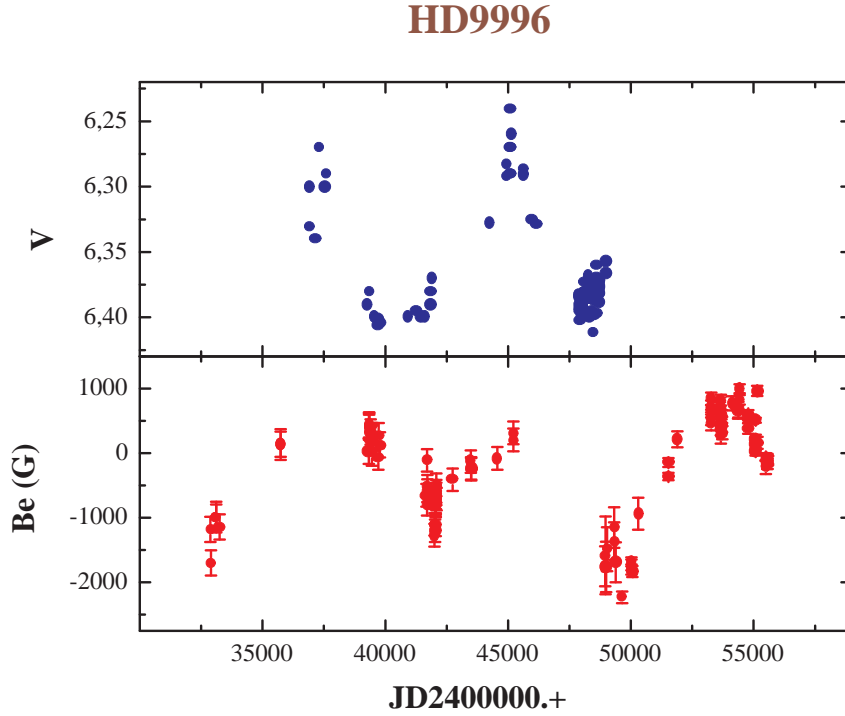


Fig. 6. Plot of all available V magnitudes for HD 9996 vs. Julian Day (*upper panel*). Clump of points on the right side denotes H_p magnitudes taken from the Hipparcos archive. *Lower panel* presents determinations of the longitudinal magnetic field B_e .

The median magnitude of HD 9996 was equal to $H_p = 6.3812$ mag at that time with modulation of the amplitude $\Delta H_p = 0.014$ mag and a period of $P_{ph} = 39.76 \pm 0.02$ days. Therefore, Hipparcos photometry seemed to confirm more uncertain results of earlier ground-based observations.

We reanalyzed time series of 93 original Hipparcos magnitudes of HD 9996 (HIP 7651), which are available at

http://www.rssd.esa.int/hipparcos_scripts/HIPcatalogueSearch.pl?hipecId=7651

Amplitude spectrum of these observations shown in Fig. 7 does not show any peak for periods $P \geq 5$ days (frequency $f \leq 0.2 \text{ days}^{-1}$) with full amplitude higher than 0.012 mag. Therefore, we reject the period of 39.76 days claimed by the Hipparcos team in our analysis.

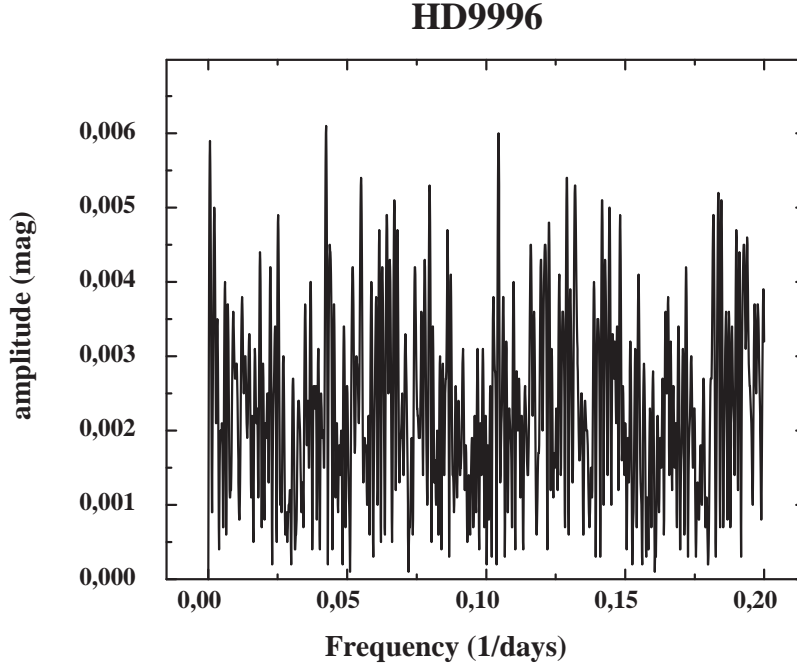


Fig. 7. Amplitude spectrum of Hipparcos H_p magnitudes. No trace of a periodic light variations is seen in this frequency range with half-amplitude exceeding 0.006 mag.

6. Rate of Rotation

We also measured half-widths of many spectral lines in our Zeeman spectra to determine or constrain projected rotational velocity of the magnetic star in HD 9996. We took into account lines in 20 spectra taken in over 17 years of observations, *i.e.*, during most of the observing period. Measurements of the half-widths of the total 8723 narrow lines showed, that HD 9996 rotates slowly and – on the average – line widths are the same as in standard stars with $v_e \sin i = 0$. Therefore, we can only set an upper limit on the projected rotational velocity on the equator

$$v_e \sin i \leq 8 \text{ km/s} \quad (4)$$

and this value is just equal to the average error of measurements.

The effective temperature of the primary Ap star was found in literature, $T_{\text{eff}} = 10000 \text{ K}$. This value implies that the radius equals to $R = 2.4 R_{\odot}$, which is valid for a main-sequence star. Preston (1971b) presented a simple relation

$$v_e = \frac{50.61 R}{P_{\text{rot}}} \quad (5)$$

where v_e , R , and P_{rot} are expressed in km/s, solar radii and days, respectively. Consequently, our extensive observations of half-widths exclude short rotational periods of HD 9996 and set

$$P_{\text{rot}} \geq 15 \text{ days.} \quad (6)$$

Our results agree with the early paper by Preston (1971a), who estimated the projected equatorial velocity for HD 9996, $v_e \sin i \leq 6 \text{ km/s}$. Resolution R of our spectra did not allow us to constrain further either $v_e \sin i$ or P_{rot} .

We should note here that Carrier *et al.* (2002) published more stringent estimate $v_e \sin i \leq 2 \text{ km/s}$, hence $P_{\text{rot}} \sin i \geq 60.7 \text{ days}$.

7. Discussion

7.1. Photometry and Magnetic Field

Spectroscopic binary star HD 9996 exhibits periodic magnetic and light variations with at least one period. Long-term light and B_e variations were displayed in Fig. 6. They are apparently correlated and perhaps proceed with the same period $P_{\text{mag}} = 21.8 \text{ years}$.

Unfortunately, there exist no reliable V magnitudes of HD 9996 obtained after the Hipparcos era. HD 9996 is a relatively bright star, therefore, all recent robotic photometric surveys like TASS, WASP and ASAS3 produced saturated images of this object and unreliable V determinations.

Hipparcos photometric data yielded the short-term period, $P_{\text{ph}} = 39.76 \text{ days}$. This is possibly is the rotational period, however, we did not confirm its existence by an independent analysis of Hipparcos observations.

7.2. Precession and Tidal Interactions

We attribute the period of $P_{\text{mag}} = 21.8 \text{ years}$ to the period of forced precession of the rotational axis of the primary Ap star in the gravitational field of the secondary. This type of precession in a binary system was proposed and studied in detail by Shore and Adelman (1976) and Lehmann (1987).

Further studies of the interaction between companion stars in HD 9996 require a model of precession and nutation of Ap star in this binary system, taking into account exact value of its moment of inertia, the latter taken from numerical models of stellar structure.

7.3. Projected Equatorial Velocity

Binary star HD 9996 possibly exhibits the following unique property. If the period of precession in the system equals $P_{\text{mag}} = 21.8 \text{ yr}$, then the inclination angle i , hence $v_e \sin i$, must also oscillate with the precession period. Detection of this effect in slowly rotating primary Ap companion in HD 9996 requires use of optical spectra of high spectral resolution for exact measurements of $v_e \sin i$ over many years.

Obviously the above effect of forced precession would be best observed when the equator velocity v_e was large enough or, consequently, when the period of rotation is short. We failed even to measure a single $v_e \sin i$ value in HD 9996 due to the slow rotation of the Ap companion and the low resolution of our spectra ($R \approx 25\,000$).

7.4. Periods of HD 9996

On the basis of the available observational data we propose the following scenario. The observed effective magnetic field B_e is the projected field of the bright Ap primary star in the binary system. Long period of magnetic variations $P_{\text{mag}} = 21.8$ years is just the precession period of the primary star in the gravitational field of the secondary, which is very faint in visual and remained unseen in the spectrum of the binary.

Light variations in the V Johnson filter are of the same time-scale as the magnetic period of 21.8 yr equal by assumption to the precession period. Note, that Rice (1988) identified a period of 21–22 yr with the rotational period.

8. Geometry of the Magnetic Field

Surface properties of the primary Ap star in HD 9996 can be explained in terms of the standard oblique-rotator model. Origin of its long-term magnetic and light variations can be attributed to the precession of the rotation axis in a gravitational field of the secondary. Both magnetic and light variations must then proceed with the same period $P_{\text{mag}} = 21.8$ yr, since both were caused by periodic variations of the aspect angle. Note, that the variability period could not be determined with such a high accuracy.

Possible short-term light variations with the period of ca. 40 days are then caused by rotation of the Ap star. In such a scenario we must assume that the magnetic axis is aligned to the stellar rotation axis. This is the only configuration consistent with a global longitudinal field that is constant as the star rotates. Such a configuration allows one to interpret the observed 21.8 years field variability in terms of precession of the star's rotation axis.

The requirement that the magnetic axis is parallel to the rotation axis would be statistically not very likely, although Landstreet and Mathys (2000) argued that slowly rotating stars tend to have the magnetic axis tilted at a small angle with respect to the rotation axis.

Our results indicate however, that the scatter of the magnetic field measurements at a given phase of the long period amounts to 200 G (see Fig. 4). Apart from the measurement errors they may (at least partly) result from modulation with the rotational period. In this case, both axes may be inclined to each other, though we did not develop a numerical code to compute models of B_e variations of the oblique rotator.

Our periodogram in Fig. 7 excluded the existence of 40 days variations in Hipparcos photometry with full amplitude bigger than 0.012 mag. The period of 39.76 days obtained by Hipparcos team could only be real with smaller amplitude, which is not unusual for Ap stars. Such a short period, if confirmed by other authors or in other colors, could be interpreted as the period of rotation.

9. Summary

In this work we presented a homogeneous series of 63 measurements of the longitudinal magnetic field B_e in the spectroscopic binary HD 9996, where the primary companion is an Ap star. Our measurements were obtained in the years 1994–2011 in the coude focus of the 1-m reflector of the Special Astrophysical Observatory, using the same spectrometer and analyzer of circular polarization during 18 years of observations. Using all available B_e points from 62 years of observations (3 full magnetic cycles), we improved the long-term magnetic period of HD 9996 and set $P_{\text{mag}} = 21.8$ years.

We performed an extensive analysis of line-widths in HD 9996 and constrained rotational velocity on the equator of the magnetic (primary) star to $v_e \sin i \leq 8 \pm 1$ km/s, or its rotational period to $P_{\text{rot}} \geq 15 \pm 2$ days.

Compilation of archival photometric data showed the existence of long-term variations of HD 9996 consistent with $P_{\text{mag}} = 21.8$ year. Photometric data from Hipparcos archive showed the short-term H_p variations with the period $P_{\text{phot}} = 39.76$ days, however, the existence of this period was not confirmed in our spectral analysis of these data. We identify P_{mag} with the precession period of the primary Ap star.

We regard the binary star HD 9996 as an important object for studies of generation, evolution and interaction of stellar gravitational and magnetic fields.

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